# AN IMPROVED MEASURE OF QUASAR ORIENTATION

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Beverley J. Wills and M. S. Brotherton
*McDonald Observatory and Astronomy Department, University of Texas, Austin, TX 78712*
*Internet: bev@astro.as.utexas.edu, msb@astro.as.utexas.edu*

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## ABSTRACT

Radio core dominance, usually measured by R, the rest frame ratio of core to lobe flux density, has been used as an indicator of Doppler boosting of quasars' radio jets and hence the inclination of the central engine's spin axis to the line of sight. The use of lobe flux density as a means of normalizing the boosted core flux density to the available intrinsic power of the central engine introduces scatter. This is because the emission from the radio lobes depends strongly on the interaction of the jet with the environment at distances beyond several Kpc from the nucleus. Total kinetic power in the extended radio emission is approximately proportional to emission line luminosity, and emission line luminosity is proportional to the luminosity of AGNs' featureless continua – both over 4 orders of magnitude. Thus, quasars' optical luminosity may be an excellent measure of available intrinsic jet power. Therefore we define a new core dominance parameter, $R_V$, the ratio of radio core to optical (rest frame V band) continuum luminosity, that is not directly dependent on jet interactions with the super-Kpc-scale environment. We show that the use of $R_V$, rather than R, results in significantly improved inverse correlations with the beaming angle as deduced from apparent superluminal velocities and inverse Compton scattered X-ray emission, and with the FWHM of quasars' broad H$\beta$ emission line. We discuss some implications and applications of the new parameter.

*Subject headings:* quasars: general — quasars: emission lines — radio continuum: general

## 1. Introduction

Different viewing angles successfully unify a wide variety of sizes and structures of extragalactic radio sources, their optical classification, and many other properties. Bright radio bright cores are believed to be simply end-on views of extended double-lobed sources with electron synchrotron emission from their weak nuclear jet Doppler-boosted $\sim 1000$-fold into a narrow cone making a small angle to the line of sight (e.g., Blandford & Rees 1978; Orr & Browne 1982; Hough & Readhead 1989). In this model, the observed jet direction near the nucleus defines the projected rotation axis of a massive central engine. The angle of the axis to the line of sight may be measured by the ratio R of flux density in a nuclear core, unresolved on arcsecond scales, to that emitted essentially isotropically from the extended radio lobes.

Because the line- and continuum-emitting central regions of distant quasars cannot be spatially resolved, the correct interpretation of radio core dominance is important, as it provides one of the few available tools for investigating the geometry of AGNs. This orientation indicator provided the basis for several statistical investigations showing axial beaming of optical and X-ray continuum emission, kinematic axisymmetry of the broad-emission line gas, probable axisymmetry of optical depth in emission line regions, obscuration, and dust reddening (e.g., Browne & Murphy 1987; Impey et al. 1991; Wills et al. 1992; Wills & Browne 1986; Jackson et al. 1989; Jackson & Browne 1991; Baker et al. 1994; Brotherton 1995).

High resolution milliarcsecond maps of jet structure and superluminal motion show relativistic velocities for knots in nuclear jets, with a typical Lorentz factor $\Gamma \sim 5$ (Vermeulen & Cohen 1994). Ghisellini et al. (1993) compared these apparent expansion speeds for about 40 AGNs, with the Doppler factor derived from inverse Compton scattering of radio photons into the X-ray regime. They showed that a simple ballistic model fits the data, and that, statistically, the Lorentz factor giving rise to these observed pattern speeds is, within the uncertainties, the same as that for the bulk velocities of the synchrotron-emitting electrons. (But see the detailed discussion by Vermeulen & Cohen 1994). Then, assuming these two speeds to be equal, they derived, for individual sources, $\Gamma$ and $\phi$, the angle of the beam to the line of sight. Ghisellini et al. showed that R appears to be an indicator of $\phi$. An updated version of this result is shown in Fig. 1a.

Ideally, one would prefer to normalize the beamed core luminosity to the intrinsic jet power. The extended radio luminosity is not necessarily the best measure of this. Recently Bridle et al. (1994) presented high dynamic range VLA maps for part of their sample of 3CR quasars, and concluded that, while the one-sided inner few kiloparsecs are dominated by relativistic beaming, the regions beyond are increasingly affected by interactions with a clumpy intergalactic medium. The lobe flux densities are as much an indication of beam power losses via interactions with the interstellar or intergalactic medium as they are an indication of the intrinsic power of the central engine.

## 2. An Improved Core Dominance Parameter

We propose a different way to normalize core luminosity using the optical luminosity as a measure of intrinsic jet power. This is strongly justified by two results in combination. First, Yee & Oke (1978) and Shuder (1981) showed that emission-line luminosity is proportional to the luminosity of the featureless continuum over four orders of magnitude, for a range of AGN types, and including the broad emission lines of radio galaxies and QSOs. Second, Rawlings & Saunders (1991) found that emission-line luminosity is approximately proportional to the total jet kinetic power for an unbiased sample of FR II radio galaxies, and that this relation holds over four orders of magnitude when high and low luminosity radio galaxies, and even broad lined quasars ($z < 1$), are included. They concluded that the luminosity of the ionizing radiation is proportional to jet kinetic power, and that both are closely coupled to the power of the central engine. The relation with narrow line luminosity is not nearly as tight when the extended radio lobe luminosity is used instead of the total jet power. We use the optical continuum luminosity as a measure of the available intrinsic jet power, rather than emission-line luminosity because the latter is known to have large intrinsic scatter – determined by differences in covering factor, distance of ionized gas from the ionizing continuum, and physical conditions.

Thus, we define, as an alternative measure of core dominance, $R_V$, the ratio of the radio core luminosity at 5GHz rest frequency to the optical V band luminosity: $\log R_V = \log(L_{core}/L_{opt}) = \log(L_{core}) + M_{abs}/2.5 - 13.69$, where $M_{abs}$ is the absolute magnitude based on K-corrected V magnitudes. We use the $M_{abs}$ values conveniently tabulated by Véron-Cetty

& Véron (1993), but correct them to $q_0 = 0$. Hereinafter we use $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$. In this *Letter*, we justify $R_V$ as an improved measure of orientation, show an application, and discuss some implications of this new parameter.

## 3. Core Dominance vs. Jet Angle

Figures 1a and 1b compare the correlations of R and $R_V$ vs. the angle between the jet and the line of sight, $\phi$, for 33 FR II radio sources. The jet angle is calculated using apparent superluminal motions from VLBI and the Doppler factor found from the ratio of radio core flux density to upper limits on the inverse Compton scattered X-ray flux density. For 29 sources we use the data and calculations given by Ghisellini et al. (1993). We include four other sources using more recently available apparent expansion speeds (Vermeulen & Cohen 1994) and *Einstein* X-ray data (Wilkes et al. 1994), deriving $\phi$ using the method of Ghisellini et al. (1993). These correlations support the use of core dominance to measure beaming angle. For R vs. $\phi$, the Spearman rank correlation coefficient, $r_s$, is $-0.45$, with a less than 0.0025 (one-tailed) probability, $P_{1t}$, of arising by chance from uncorrelated variables. Two-tailed probabilities are given in Table 1. The use of $R_V$ significantly reduces the scatter ($r_s = -0.69$, $P_{1t} < 10^{-5}$); it can be seen that the greatest variation in $R_V$ is explained by the relativistic beaming model, and intrinsic variation in jet luminosity or even $\Gamma$ must be small by comparison. While the sample is incomplete, and core flux density is used directly in calculating R and $R_V$, and indirectly in calculating $\phi$ (through the limits on Inverse Compton scattering), the correlation is not strongly affected by this. To demonstrate this we tested the corresponding correlations with the superluminal velocity $\beta_{apparent}$, which is derived from observational quantities that are independent of core-dominance. For R the correlation is significant at the $P_{1t} \sim 10\%$ level, compared with $< 1\%$ for $R_V$. The fact that $R_V$ improves the relations for both $\beta_{apparent}$ and $\phi$, while both R and $R_V$ are uncorrelated with $\Gamma$ (Table 1) supports both the relativistic beaming model and the use of $R_V$ as an orientation indicator.

## 4. Core Dominance vs Broad Line Widths

Figure 2 shows correlations between the width of the broad H$\beta$ emission line and the measures of core dominance (R and $R_V$) for two samples of low z quasars investigated by Wills & Browne (1986, hereafter WB86) and Brotherton (1995; hereafter B95). There are $\sim$40 objects in common. The correlation is significantly improved for both samples when $R_V$ is used (Table 1). The improvement with $R_V$ is not the result of a correlation between line width and optical luminosity; there is no significant correlation of FWHM with either optical or extended radio luminosity. We interpret the improvement with $R_V$ instead of R as the result of avoiding the large intrinsic scatter of normalizing the core luminosity by the extended radio luminosity.

Because the relationship between FWHM and core-dominance has been significantly tightened, FWHM must depend on whatever determines the wide range in $R_V$. The results of §3 suggest that this is orientation rather than intrinsic core power.

Wills & Browne (1986) attributed the inverse correlation between FWHM and R to geometric projection of an axisymmetric velocity field. Osterbrock (1977) had earlier suggested projection to account for the wide range in line widths of Seyfert 1 galaxies, despite their similar physical conditions (line ratios). More recently Brotherton et al. (1994) found strong relationships between broad-line ratios and line widths for QSOs showing that, for UV lines, FWHM is often determined by varying relative contributions of two or more kinematically distinct emission regions with different physical conditions. This was reinforced for H$\beta$ by B95 who found, using principal component analysis, that the most straightforward interpretation is that a very broad (9000 km s$^{-1}$), component is strong in lobe-dominant sources and weak in core-dominant sources.

## 5. Discussion

The use of optical continuum luminosity rather than extended radio luminosity to represent the unbeamed jet power probably works better because the latter is affected by source-to-source differences in jet interaction with an inhomogeneous intergalactic medium. Optical continuum luminosity may plausibly be proportional to the intrinsic (unbeamed) power of the radio jets if it arises from accretion onto a massive compact object whose rotation powers the radio jets. This hypothesis is consistent with the improved correlations – a result that must be included in devising a model for quasars' central engines. A corollary to this is that the ratio of extended radio luminosity to

optical continuum luminosity could be a useful probe of the interstellar medium, the intergalactic medium, or galaxy cluster environment of AGNs, beyond several Kpc from the central engine.

There are some additional reasons to believe that the new parameter is an improvement on R. $R_V$ may be less affected by long-timescale variability, since radio core and optical luminosity arise within the nucleus, whereas the extended radio emission is a longterm time-averaged representation of the central engine power. Also, $R_V$ is more easily obtained in many cases. It is easier to determine an optical luminosity than an extended radio luminosity for low redshifts, especially where extended lobe emission may be resolved. At higher redshifts, a lobe structure is more difficult to define because of increasing interaction with the environment (e.g., Barthel, Tytler, & Thompson 1990), but core luminosity may still be obtained. The correlations might be improved by obtaining more accurate optical photometry, preferably simultaneous with the radio core flux densities.

Figure 3 directly compares R and $R_V$ using objects from both B95 and WB86. The two measures differ approximately by a constant factor: $\log R = \log R_V^{1.10\pm0.08} - 2.7 \pm 0.2$ (using the ordinary least squares bisector as computed by Isobe et al. 1989).

There are some limitations to the use of the optical continuum as a normalization factor. One should exclude the beamed synchrotron emission present in most core-dominant quasars. This correction is not easy to make, but, fortunately, if broad emission lines are clearly present, as for the objects in the samples used here, then the unbeamed continuum dominates, and the correction is small. This correction may move some of the highest R points to higher $R_V$ in Figure 3. The non-synchrotron continuum may not be isotropic, for example, if it is emitted from from an accretion disk or its corona. Figure 3 shows $R \propto R_V$, so there is no strongly axisymmetric emission. One could correct the optical continuum for reddening in cases of dusty quasars or radio galaxies. In practice, this may be difficult. Choosing an infrared continuum may reduce this problem (e.g., Spignolio & Malkan 1989). Also, a monochromatic optical luminosity may not accurately reflect intrinsic luminosity if there are object-to-object differences in spectral shape (see Netzer et al. 1995; Spignolio & Malkan 1989). In cases where the true optical continuum cannot be determined, such as for dusty radio galaxies or extreme blazars, one can use R together with the relation of Fig. 3 to calculate an effective $R_V$.

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Table 1
Spearman Rank Corrlelations[a]

| | R | $R_V$ |
|---|---|---|
| $\phi$ (VLBI sample) | $-0.45$ | $-0.69$ |
| | 0.008 | $10^{-5}$ |
| $\beta_{\rm apparent}$ (VLBI sample) | 0.32 | 0.46 |
| | 0.07 | 0.007 |
| $\Gamma$ (VLBI sample) | 0.33 | 0.19 |
| | 0.06 | ... |
| FWHM H$\beta$ (B95) | $-0.37$ | $-0.59$ |
| | 0.004 | $< 10^{-5}$ |
| FWHM H$\beta$ (WB86) | $-0.34$ | $-0.53$ |
| | 0.004 | $< 10^{-5}$ |
| $L_{core}$ (B95) | 0.62 | 0.81 |
| | $< 10^{-6}$ | $< 10^{-6}$ |
| $L_{core}$ (WB86) | 0.72 | 0.83 |
| | $< 10^{-6}$ | $< 10^{-6}$ |
| $L_{ext}$ (B95) | $-0.46$ | 0.01 |
| | $< 10^{-3}$ | ... |
| $L_{ext}$ (WB86) | $-0.23$ | 0.13 |
| | 0.05 | ... |
| $M_{abs}$ (B95) | $-0.04$ | $-0.07$ |
| | ... | ... |
| $M_{abs}$ (WB86) | $-0.14$ | $-0.08$ |
| | ... | ... |

[a]Spearman rank correlation coefficients are tabulated with the two-tailed probability of such a correlation arising by chance given beneath (when $< 0.1$). The VLBI sample has 33 objects, B95 has 58, and WB86, 71 objects.

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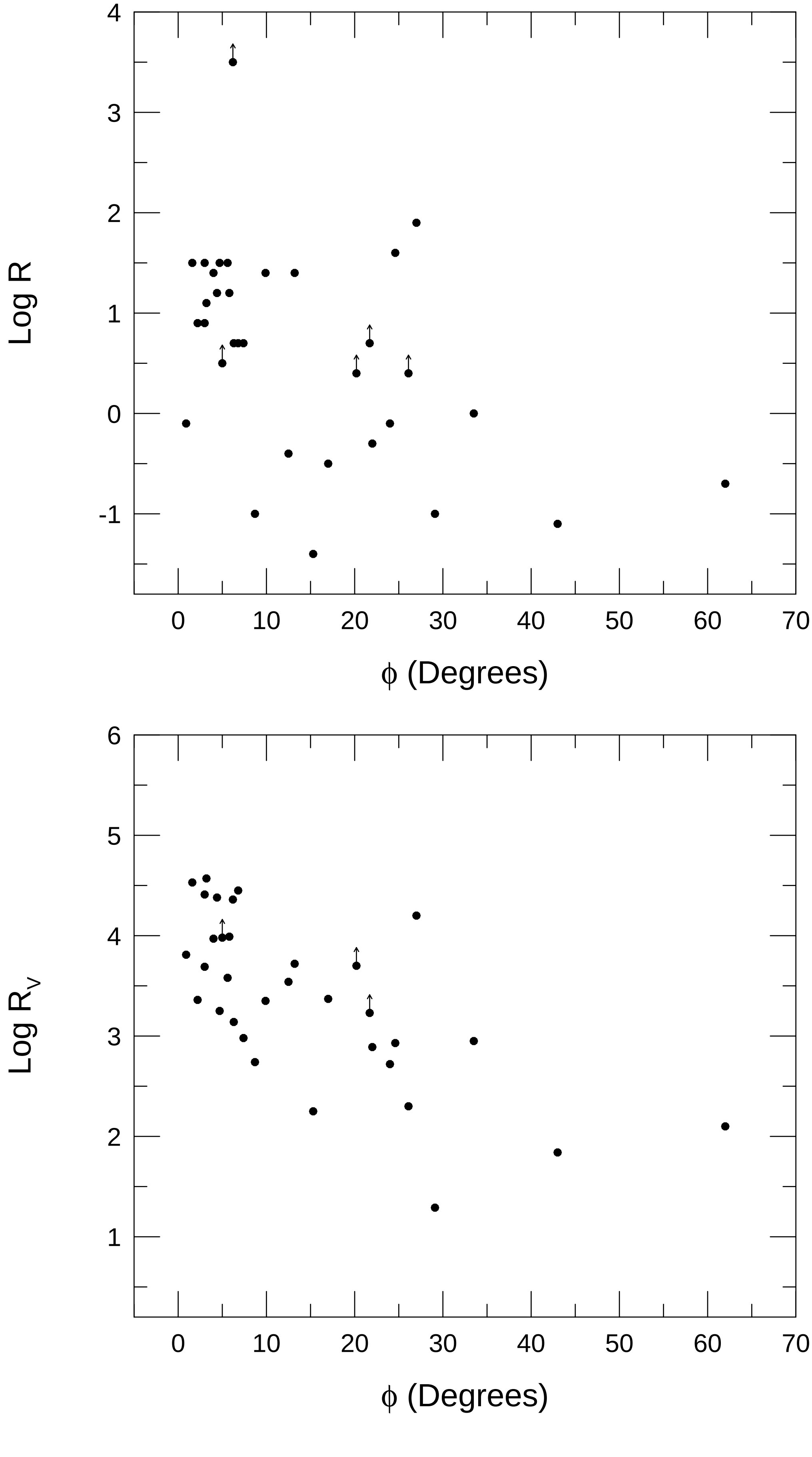
## Figure Captions

FIG. 1. The core dominance measures R and $R_V$ vs. the beaming angle $\phi$ for FR II radio sources, from Ghisellini et al. (1993). Also included are more recent observations (Vermeulen & Cohen 1994), for which we have derived $\phi$ in the same manner as Ghisellini et al.

FIG. 2. A comparison of the correlations between Log FWHM H$\beta$ (km s$^{-1}$) and core dominance for both R and $R_V$, for the data of Brotherton (1995) and the radio-loud quasars of Wills & Browne (1986) (a small number of line widths are for Mg II $\lambda$2798 instead of H$\beta$). Arrows indicate limits, filled circles indicate log R $> 0$, and open circles indicate log R $< 0$.

FIG. 3. A direct comparison of R and $R_V$ for the quasars in Fig. 2. The dotted lines indicate the ordinary least squares (OLS) fits of y on x and x on y, computed assuming that the limits are detections.


4
3
2
1
0
-1
Log R
0
10
20
30
40
50
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70
ϕ (Degrees)
6
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Log $R_V$
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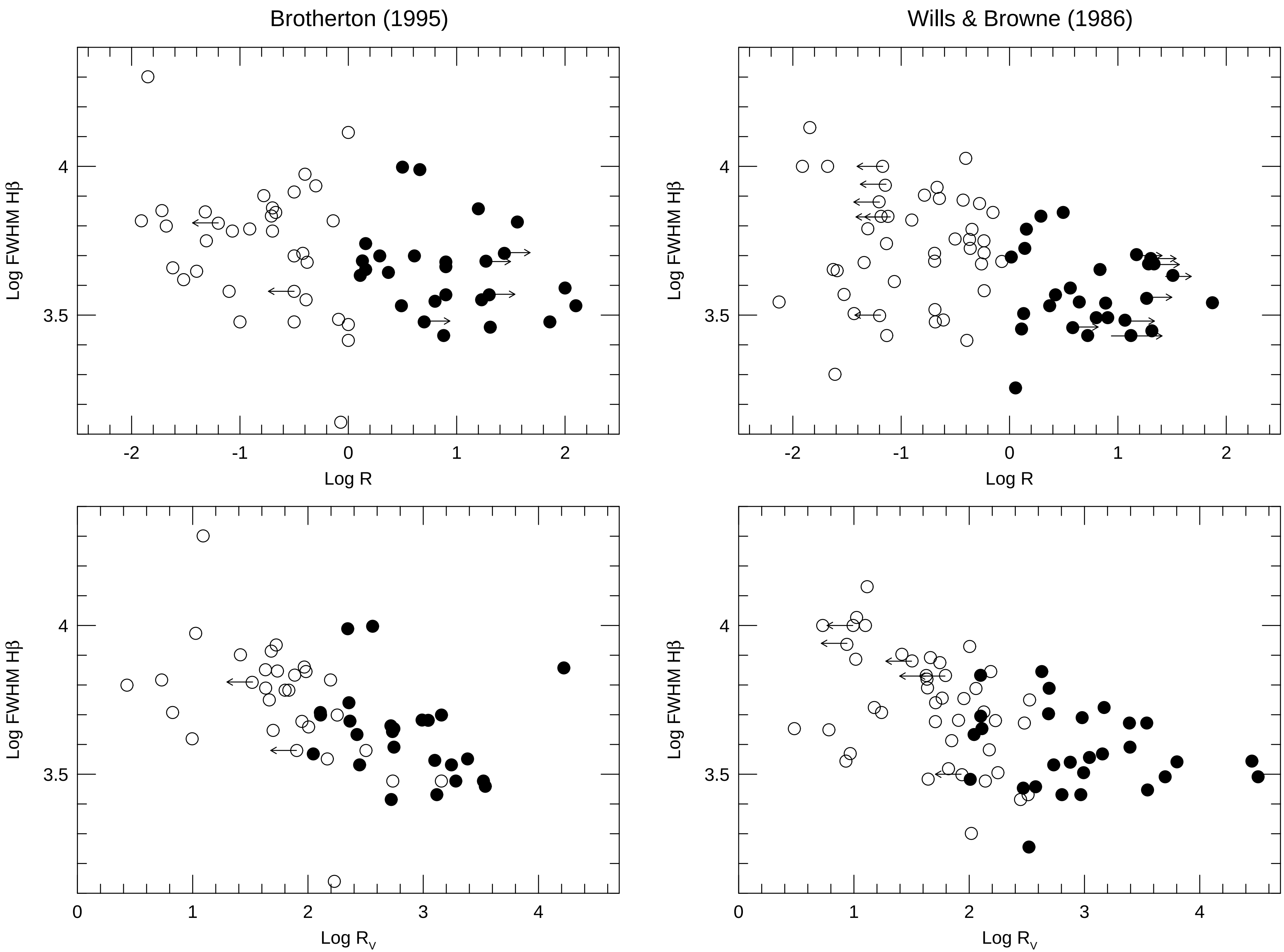
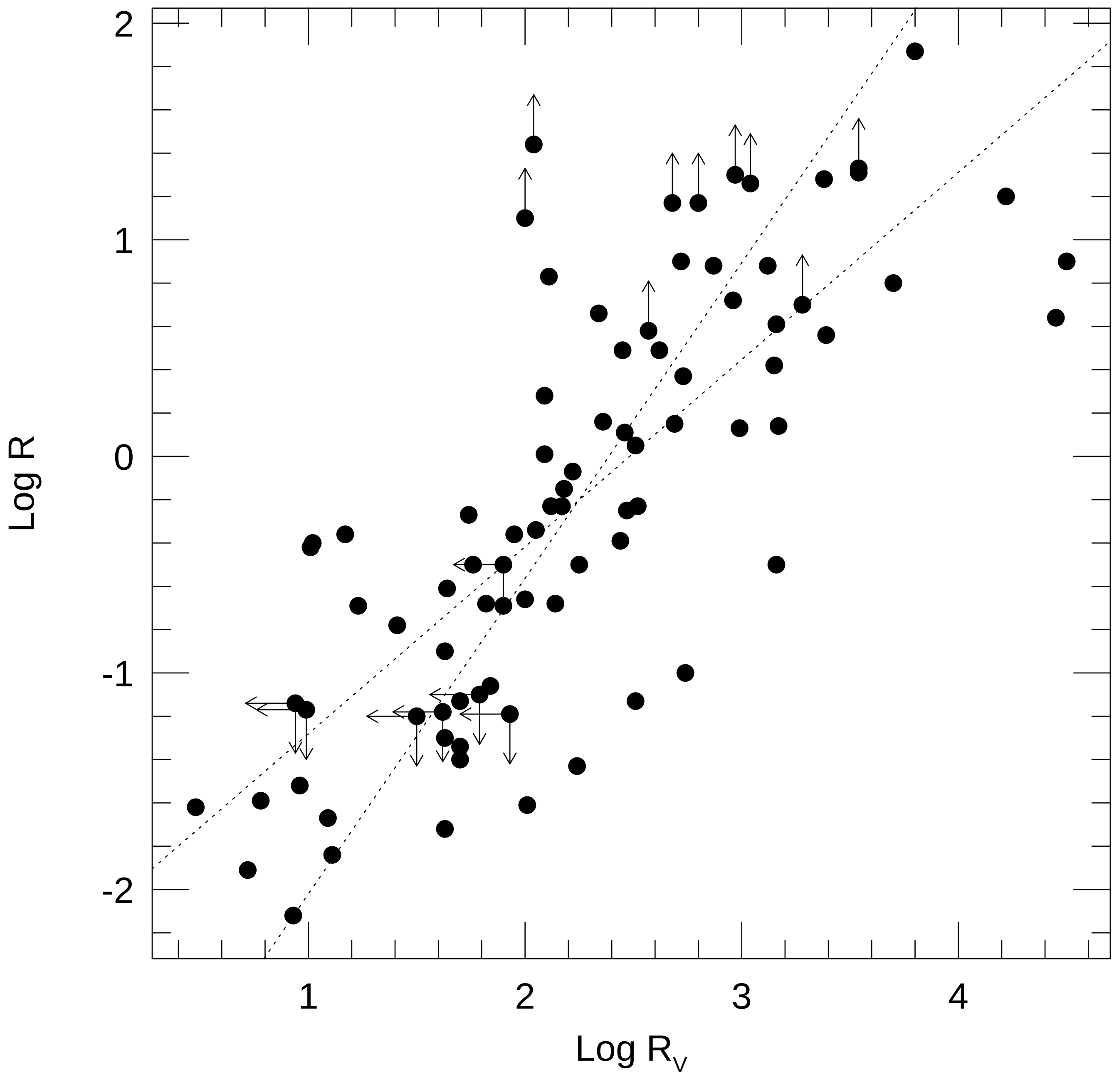
ϕ (Degrees)



Brotherton (1995)
Wills & Browne (1986)
Log FWHM Hβ
Log R
Log $R_V$
4
3.5
-2
-1
0
1
2
3
4



2
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0
-1
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2
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4
Log R
Log $R_V$